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Development of a continuous soil moisture accounting procedure for curve number methodology and its behaviour with different evapotranspiration methods

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Abstract:

The curve number (CN) method is widely used for rainfall–runoff modelling in continuous hydrologic simulation models. A sound continuous soil moisture accounting procedure is necessary for models using the CN method. For shallow soils and soils with low storage, the existing methods have limitations in their ability to reproduce the observed runoff. Therefore, a simple one-parameter model based on the Soil Conservation Society CN procedure is developed for use in continuous hydrologic simulation. The sensitivity of the model parameter to runoff predictions was also analysed. In addition, the behaviour of the procedure developed and the existing continuous soil moisture accounting procedure used in hydrologic models, in combination with Penman–Monteith and Hargreaves evapotranspiration (ET) methods was also analysed. The new CN methodology, its behaviour and the sensitivity of the depletion coefficient (model parameter) were tested in four United States Geological Survey defined eight-digit watersheds in different water resources regions of the USA using the SWAT model. In addition to easy parameterization for calibration, the one-parameter model developed performed adequately in predicting runoff. When tested for shallow soils, the parameter is found to be very sensitive to surface runoff and subsurface flow and less sensitive to ET. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS curve number; soil moisture; SWAT; HUMUS; evapotranspiration; ET; Hargreaves; Penman–Monteith

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INTRODUCTION

The curve number (CN) method (SCS, 1956) is widely used for estimating storm runoff from rainfall. It is an infiltration loss model, which does not account for long-term losses such as evaporation and evapotranspiration (Ponce and Hawkins, 1996). Interception, surface storage, infiltration, evaporation and evapotranspiration are the hydrologic abstractions that occur during the conversion of rainfall to runoff. Among these various hydrologic abstractions, infiltration is the most important for storm analysis. Evaporation and evapotranspiration are important for long-term and short-term seasonal or annual yield evaluations. Interception and surface storage are usually of secondary importance (Ponce and Hawkins, 1996). Since the CN method is an infiltration loss model that does not account for evaporation and evapotranspiration, its use was shown to be restricted to modelling storm losses and associated surface runoff (Boughton, 1989). However, the method has been used in several long-term hydrologic simulation models with an appropriate soil moisture accounting procedure (Huber *et al.*, 1976; Williams and LaSeur, 1976; Knisel, 1980; Sharpley and Williams, 1990; Arnold *et al.*, 1993; Williams *et al.*, 2000).

A sound soil moisture accounting procedure in combination with the CN procedure is needed to predict runoff from rainfall realistically, because CN is not a constant, but varies from event to event. Under wet soil conditions, much of the rainfall is converted to runoff. Therefore, the CN value has to be high for realistic prediction of runoff. On the other hand, under dry conditions the rainfall–runoff relationship is affected by the character of rainstorm and watershed conditions (Hjelmfelt, 1991). A sound soil moisture accounting procedure has to incorporate all the above-mentioned conditions. Over a period of several years, different soil moisture accounting procedures have been developed and incorporated into hydrologic modelling tools (Sharpley and Williams, 1990; Arnold *et al.*, 1993; Williams *et al.*, 2000). One such soil moisture accounting procedure developed for the use of the CN method for continuous hydrologic modelling in the Soil and Water Assessment Tool (SWAT; Arnold *et al.*, 1993) and Agricultural Policy/Environmental Extender (APEX) (Williams *et al.*, 2000) is discussed in this article. In addition, the sensitivity of different water balance components to the parameter of this method, the behaviour of the method in combination with different evapotranspiration estimation methods are also discussed. The commonly used

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soil moisture accounting procedure (existing/previously developed) in SWAT and APEX overestimates runoff in shallow soils and soils with low storage. For better estimation of runoff under those situations, the present soil moisture accounting procedure is developed.

BACKGROUND

The CN runoff equation is given by

$$Q = \frac{(P - 0{\cdot}2S)^2}{P + 0{\cdot}8S} \tag{1}$$

where Q is the depth of runoff, P is the depth of rainfall and S is a retention parameter. The retention parameter is related to the CN as follows:

$$S = \frac{1000}{\text{CN}} - 10 \tag{2}$$

The value of S in the CN method is related to watershed features and antecedent moisture conditions. To be used in continuous hydrologic modelling, the parameter S should be linked to a sound continuous soil moisture accounting procedure. Most of the existing models (e.g. SWAT, EPIC, APEX) use a procedure that links S with available soil water capacity of soil and use the CN methodology in continuous simulation. The model predictions of runoff will be more realistic if the parameter S is linked to soil moisture depletion, rather than to soil available water capacity. Williams and LaSeur (1976) were the first to incorporate this idea in the CN method (Equations (3)–(5)). The model has an upper limit (508 mm) for moisture storage in soil. This method avoids sudden jumps in CN from one moisture condition to another and yet allows CN values to vary widely from 33·3 to 100. The model calibration is based on the adjustment of depletion coefficient B (Equation (4)) until the predicted average annual surface runoff closely matches the observed value. One year of rainfall–runoff data is used to get a realistic initial estimate of soil moisture. Arbitrary fixing of a maximum value of moisture storage in the soil V and a loss of 1 year's rainfall–runoff information can be viewed as the limitations of this method (Mishra and Singh, 2004):

$$\text{SM} = V - S \tag{3}$$

where SM is the soil moisture index.

$$\text{SM}_t = \frac{\text{SM}}{1{\cdot}0 + B \times \text{SM} \sum_{t-1}^{T} \text{PET}_t} \tag{4}$$

where SM_t is the soil moisture index at any time t, B is the moisture depletion coefficient and PET_t is the average monthly lake evaporation for day t.

Hawkins (1978) related evapotranspiration ET and CN and formulated a continuous soil moisture accounting procedure for the use of the CN methodology in continuous hydrologic simulation. The relationship is given by

$$\text{CN}_t = \frac{1200}{\left(\dfrac{1200}{\text{CN}_{t-1}}\right) + [\text{ET} - (P - Q)]_t} \tag{5}$$

where CN_t is the CN at time t, CN_{t-1} is the CN at the previous time step, ET is evapotranspiration at time t, P is rainfall depth at time t and Q is runoff depth at time t.

Similar to the soil moisture accounting procedure developed by Williams and LaSeur (1976), the procedure developed by Hawkins (Equation (5)) avoids sudden jumps in CN value from one moisture condition to another. However, it allows an additional storage space of 20% of S available for water retention at every time interval, which in turn results in negative infiltration under no-rainfall conditions (Mishra and Singh, 2004).

Recently, Mishra and Singh (2004) proposed a model for the CN methodology involving four parameters (a parameter for the static portion of infiltration amount, a storage coefficient, a base flow storage coefficient, and a potential maximum retention parameter). The model parameters can be derived either physically or from rainfall–runoff data. The model was applied to the Hemavati watershed in India and found to give satisfactory results for monthly and annual runoff (Mishra and Singh, 2004).

Although the method proposed by Mishra and Singh (2004) is proved to work well, it requires estimation and calibration of four parameters, which might be difficult under most modelling situations. Considering the limitations of the previous methodologies, an alternate methodology is proposed (Williams *et al.*, 2000) and is given in Equation (6). Operation of the model, sensitivity of the model parameter and the behaviour of the proposed method with different evapotranspiration methods are discussed in this article:

$$S_t = S_{t-1} + \text{PET}_t \exp\left(\frac{-BS_{t-1}}{S_{\max}}\right) - P + Q \tag{6}$$

where S_t is the retention parameter at the present time step, S_{t-1} is the retention parameter at the previous time step, B is the depletion coefficient (theoretically varies from 0 to 2), P is the rainfall depth at the previous time step, Q is the runoff depth at the previous time step, and $S_{\max}$ is the maximum value of the retention parameter.

MODEL OPERATION AND CALIBRATION

An initial estimate of S is obtained based on the existing value of CN_2 (condition II CN). The maximum value of the retention parameter $S_{\max}$ is obtained by substituting CN_1 (condition I CN, which can be derived from CN_2) in Equation (2). The initial estimate of runoff is obtained using the values of S and P in Equation (1). During a rainfall event, the retention parameter is calculated (using Equation (6)) as the sum of the initial estimate of S_{t-1}, potential evapotranspiration (PET) at the present

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time, an exponential function of S_{t-1}, S_{max}, the depletion coefficient, and the amount of rainfall that infiltrates $(P - Q)$. Having found a new estimate for S (i.e. S_t), Q can be estimated by substituting S_t for S and P in Equation (1). Equation (6) is designed to deplete S at a faster rate as S approaches zero (soil water is near saturation) (Equations (7) and (8)) and at a much slower rate as S approaches S_{max} (very dry) (Equation (9)).

Substituting $S_{t-1} = 0$ in Equation (6) yields

$$S_t = 0 + \mathrm{PET}_t \exp\left(\frac{-B \times 0}{S_{max}}\right) - P + Q \qquad (7)$$

$$S_t = \mathrm{PET}_t - P + Q \qquad (8)$$

In Equation (8), retention at the present time step is a function of PET, P and Q only, i.e. less water is retained and more depleted. In other words, depletion occurs at a faster rate under saturation. Similarly, substituting $S_{t-1} = S_{max}$ in Equation (6) yields

$$S_t = S_{max} + \mathrm{PET}_t e^{-B} - P + Q \qquad (9)$$

The model calibration involves the adjustment of the depletion coefficient B until the predicted average basin/sub-basin surface runoff matches closely with that observed.

SENSITIVITY OF MODEL PARAMETER

Depletion coefficient B is the only parameter associated with the newly developed soil moisture accounting procedure in the CN methodology (hereafter described as the new CN method). The sensitivities of the various water balance components, such as surface runoff, subsurface flow, evapotranspiration and water yield, to the depletion coefficient are described here. Although the depletion coefficient varies from 0 to 2 theoretically, the practical lower and upper bounds are 0·5 and 1·5 respectively, which is adequate to capture the trends of surface runoff for most of the watersheds (Jimmy Williams, Blackland Research and Extension Center, Temple, TX, USA, personal communication, June 2006). However, a range of 0–2 is used for B for the sensitivity analysis. To demonstrate the results of the sensitivity of the depletion coefficient, the Hargreaves ET estimation method is used.

DIFFERENT COMBINATIONS OF CURVE NUMBER AND EVAPOTRANSPIRATION METHODS

Distributed parameter models used for hydrologic modelling have options for choosing different methodologies for runoff modelling and evapotranspiration estimation. After identifying the appropriate model, the selection of the right combination of runoff modelling and evapotranspiration becomes crucial in obtaining acceptable results from the model. This section of the paper describes the procedure we used to analyse the behaviour of different evapotranspiration methods in combination with different CN methods within a semi-distributed continuous simulation river-basin-scale model, i.e. SWAT. Three different methods are available in SWAT for estimating evapotranspiration. They are (1) Hargreaves, (2) Penman–Monteith and (3) Priestley–Taylor. Among these three methods, the Priestley–Taylor method was not considered for the analysis because the estimated ET values from this method seem to be too low (Kannan *et al.*, 2007). Therefore, two ET methods (namely Hargreaves and Penman–Monteith) and two CN methods (with the existing and newly developed soil moisture accounting procedures) were tested in four possible combinations. A 31-year simulation (1960–1990 with a 1-year warm-up period for the model) was performed. Four hydrologic unit catalogues (HUCs) in major river basins (or hydrologic regions) of the USA, namely 01 030 002 (New England), 03 090 204 (South Atlantic Gulf), 12 090 109 (Texas Gulf) and 14 070 005 (Upper Colorado) (Figure 1, Table I), were selected for this study. The HUCs selected

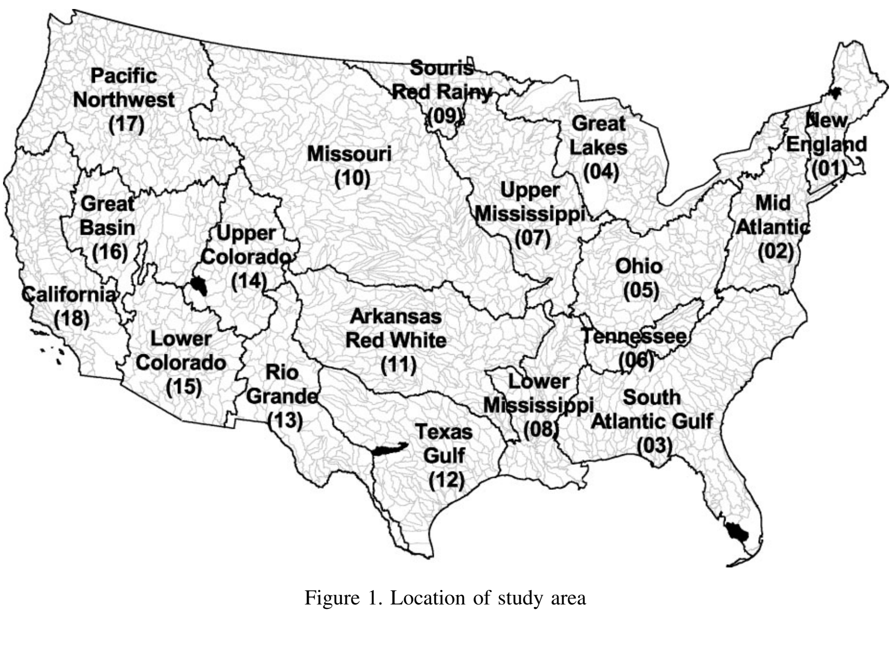

Figure 1. Location of study area

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Table I. Characteristics of study area

Region	HUC	Mean annual precipitation (mm)	Depth of soil[a] (mm)	Proportion of watershed under shallow soils (%)	Calibrated depletion coefficient[b]
New England	01030002	1052	460	93	0·40
South Atlantic Gulf	03090204	1291	—[c]	—	0·63
Texas Gulf	12090109	614	380–760	95	0·84
Upper Colorado	14070005	292	280	20	—

[a] The depth of shallow soil alone is indicated.
[b] Corresponds to the calibrated best results (highlighted) in Table II.
[c] Sandy soils with low storage.

vary in terms of land cover, climate, area covered by cultivation and hydrologic behaviour and, therefore, provide an opportunity to test the new CN procedure under different hydrological conditions. It should be noted that the focus of this article is to analyse the behaviour of different combinations of ET and CN methods in predicting surface runoff, subsurface flow and water yield, not to match the predictions and observations of flow. However, each combination of ET and CN method is individually calibrated using manual adjustment of parameters (there are more details in the 'Calibration' section).

MODELLING FRAMEWORK

For this study, the revised HUMUS/SWAT (Hydrologic Unit Modeling for the United States) modelling framework (Srinivasan *et al.*, 1998, Santhi *et al.*, 2005), comprised of SWAT with updated databases for the 18 major river basins in the USA, was used (Figure 1). HUMUS was designed for making assessments of national and river basin-scale water demands and land management practices affecting the pollution of rivers.

The SWAT model

The SWAT model (Arnold *et al.*, 1993; Gassman *et al.*, 2004; Neitsch *et al.*, 2004; http://www.brc.tamus.edu/swat/index.html) is developed to quantify the impact of land management practices on surface water quality in large, complex catchments (SWAT model version 2005 is used for this study). It provides a continuous simulation of hydrological processes (evapotranspiration, surface runoff, percolation, return flow, groundwater flow, channel transmission losses, pond and reservoir storage, channel routing and field drainage), crop growth and material transfers (soil erosion, nutrient and organic chemical transport and fate). The model can be run with a daily time step, although sub-daily data can also be used. It incorporates the combined and interacting effects of weather and land management (e.g. irrigation, planting and harvesting operations and the application of fertilizers, pesticides or other inputs). SWAT divides the watershed into subwatersheds using topography. Each subwatershed is divided into hydrological response units (HRUs), which are unique combinations of soil and land cover. Although individual HRUs are simulated independently from one another, the predicted water and material flows are routed within the channel network, which allows for large catchments with hundreds or even thousands of HRUs to be simulated.

DATABASES

The HUMUS/SWAT system requires several databases, such as land use, soils, management practices and weather. For the present study, recently available data are processed to update the HUMUS/SWAT databases and prepare the SWAT input files for the river basins (Santhi *et al.*, 2005).

Land use

The 1992 United States Geological Survey (USGS) National Land Cover Data (NLCD) are the spatial data currently available for land use at 30 m resolution for the USA (Vogelmann *et al.*, 2001). For this study, the 1992 USGS land cover data set is used as the base, which includes agriculture, urban, pasture, range, forest, wetland, barren and water.

Soils

Each land use within an eight-digit watershed (HUC) is associated with soil data. Soil data required for SWAT were processed from the State Soil Geographic (STATSGO) database (USDA–NRCS, 1994). Each STATSGO polygon contains multiple soil series and the aerial percentage of each soil series. The soil series with the largest area was extracted and the associated physical properties of the soil series were extracted for SWAT (Santhi *et al.*, 2005).

Topography

Topographic information on accumulated drainage area, overland field slope, overland field length, channel dimensions and channel slope were derived from the digital elevation model (DEM) data of the previous HUMUS project (Srinivasan *et al.*, 1998).

Management data

Management operations, such as planting, harvesting, applications of fertilizers, manure and pesticides and irrigation water and tillage operations, along with timings or potential heat units, are specified for various land uses

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in the management files. Management operations/inputs vary across regions. These data are gathered for land uses such as horticulture, pasture and hay that are simulated in SWAT from various sources such as Agricultural Census Data and the USDA–National Agricultural Statistics Service's agricultural chemical use data (Santhi *et al.*, 2005).

Weather

Measured daily precipitation and maximum and minimum temperature data sets from 1960 to 1990 are used in this study. The precipitation and temperature data sets are created from a combination of point measurements of daily precipitation and temperature (maximum and minimum) (Eischeid *et al.*, 2000) and the parameter-elevation regressions on independent slopes model (PRISM; Daly *et al.*, 1994, 2002). The point measurements compose a serially complete (without missing values) data set processed from the National Climatic Data Center station records. PRISM is an analytical model that uses point data and a DEM to generate gridded estimates of monthly climatic parameters. PRISM data are distributed at a resolution of approximately 4 km^2. A novel approach has been developed to combine the point measurements and the monthly PRSIM grids to develop the distribution of the daily records with orographic adjustments over each USGS eight-digit watershed (Di Luzio *et al.*, 2007). Other data, such as solar radiation, wind speed and relative humidity, are simulated using the weather generator (Nicks, 1974; Sharpley and Williams, 1990) available within SWAT.

CALIBRATION

The average annual observations of four HUCs from different water resource regions of the USA (Figure 1, Table I) are used for calibrating the model results. The objective of calibration was to obtain modelled results to match the observations within a difference of 20%, 10%, and 10% for water yield, surface runoff and subsurface flow respectively. The calibration was carried out manually by a trial-and-error procedure using the parameters CN, depletion coefficient, minimum depth of water in soil for base flow to occur (GWQMN), groundwater re-evaporation coefficient (GWREVAP), and threshold depth of water in the shallow aquifer for 'revap' or percolation to the deep aquifer to occur (REVAPMN) based on Neitsch *et al.* (2004) and Kannan *et al.* (2007). Although it is possible to include a few other parameters for calibration, it was decided to restrict the number of parameters to a few because of the manual adjustment of parameters.

RESULTS

Sensitivity analysis

The annual average model results of eight-digit watersheds 01 030 002 (New England region) and 12 090 109 (Texas Gulf region) were chosen for the sensitivity analysis. For HUC 01 030 002, the relationship between depletion coefficient and predicted surface runoff is direct. An increase in the depletion coefficient results in a corresponding increase in the predicted surface runoff (Figure 2a). The proportion of increase in surface runoff for a corresponding increase in depletion coefficient suggests that surface runoff is very sensitive to this parameter (Figure 2a). Similar results were obtained for HUC 12 090 109 in the Texas Gulf region (Figure 2b). From Figure 2 it can be observed that subsurface flow is also sensitive to the depletion coefficient parameter. An increase in the parameter causes a decrease in the predicted subsurface flow (Figure 2a and b). The pattern of sensitivity exhibited by the parameter to subsurface flow is simply the opposite of the sensitivity to surface runoff. The other interesting fact is that an increase or decrease in the depletion coefficient does not significantly alter the predicted ET or water yield values (Figure 2a and b). Therefore, once the total water yield is modelled reasonably, the proportion of subsurface flow and surface runoff can be adjusted for a subwatershed/watershed simply by adjusting the depletion coefficient, which makes the parameterization easy.

Which curve number method is better for shallow and low-storage soils?

A summary of the results from the four HUCs selected is given in Table II. The values highlighted in bold indicate the best possible calibrated results for a particular HUC. Based on the best results for each HUC we can understand that the new CN method outperformed the existing CN method by means of providing better results in calibration. This behaviour is clearly visible from the results of HUCs 03 090 204 (low-storage soils) and 12 090 109 (shallow soils), which indicate a significantly better performance of new CN method over the existing CN method. The poor performance of the existing CN method under these conditions can be attributed to the overestimation of surface runoff and water yield by the existing CN method, whereas it is appropriately modelled by the new CN method. Although HUC 01 030 002 also shows better performance with the new CN method over the existing CN method, the difference is only marginal. In contrast to the above discussion, the results from HUC 14 070 005 indicate that the existing CN method gives better results than the new CN method. The following reasons could be attributed for this behaviour. (1) Unlike the other HUCs, only 20% of this HUC has shallow soils. Although it was in the interest of this study to observe the behaviour of the new CN method in a combination of shallow soils and very low rainfall conditions, the selection of an appropriate HUC with a major portion under shallow soils was not possible. (2) Prediction of runoff in the new CN method is mainly based on the depletion coefficient parameter, which in turn is based on PET and precipitation. The average annual precipitation for HUC 14 070 005 is only 292 mm, which is too low when compared with the precipitation of the other HUCs

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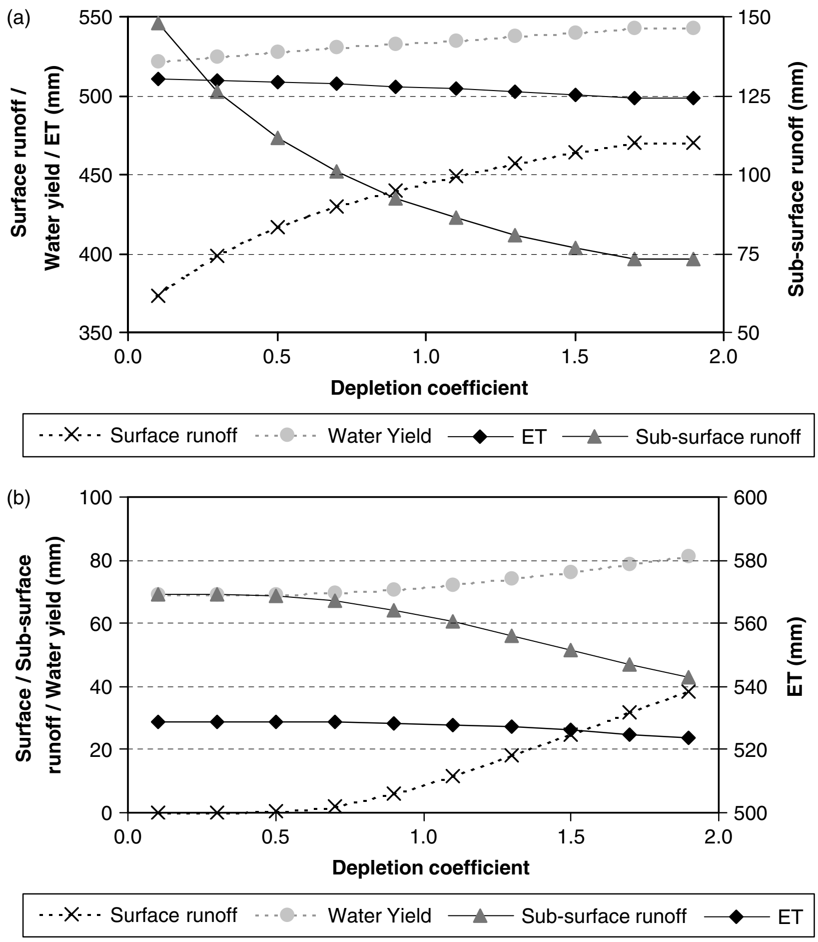

Figure 2. Sensitivity of depletion coefficient to different water balance components: (a) HUC 1 030 002; (b) HUC 12 090 109

Table II. Calibrated average annual results for different ET and CN combinations[a]

Method	ET (mm)	Surface runoff (mm)	Subsurface runoff (mm)	Water yield (mm)	Difference (%) between predictions and observations in:		
					Surface runoff	Subsurface runoff	Water yield
Results for HUC 01 030 002 (annual mean precipitation: 1051·5 mm)							
Observed/target		291·7	331·1	622·9			
Penman–Monteith, new CN	**475·2**	**312·0**	**267·7**	**579·7**	**6·9**	**−19·1**	**−6·9**
Penman–Monteith, old CN	476·1	315·7	261·7	577·4	8·2	−21·0	−7·3
Hargreaves, new CN	510·7	373·6	169·4	543·0	28·0	−48·8	−12·8
Hargreaves, old CN	514·7	305·3	232·3	537·6	4·7	−29·8	−13·7
Results for HUC 03 090 204 (annual mean precipitation: 1290·6 mm)							
Observed/target		105·9	135·5	241·4			
Penman, new CN	712·8	112·2	193·4	305·6	6·0	42·7	26·6
Penman–Montieth, old CN	711·8	152·1	171·6	323·7	43·6	26·7	34·1
Hargreaves, new CN	**1008·8**	**108·4**	**146·6**	**255·0**	**2·3**	**8·2**	**5·6**
Hargreaves, old CN	1010·7	113·9	141·1	255·0	7·5	4·1	5·6
Results for HUC 12 090 109 (annual mean precipitation: 613·9 mm)							
Observed/target		8·5	5·7	14·2			
Penman–Monteith, new CN	**497·1**	**8·1**	**5·9**	**13·9**	**−4·6**	**2·0**	**−1·9**
Penman–Monteith, old CN	494·6	53·9	6·1	60·0	535·7	6·6	321·9
Hargreaves, new CN	528·1	8·9	6·0	14·9	4·5	4·8	4·6
Hargreaves, old CN	524·1	47·2	5·6	52·8	456·9	−2·5	271·2
Results for HUC 14 070 005 (annual mean precipitation: 292·3 mm)							
Observed/target		11·4	16·1	27·5			
Penman–Monteith, new CN	236·2	1·0	15·6	16·6	−91·2	−2·9	−39·6
Penman–Monteith, old CN	**236·1**	**11·2**	**14·8**	**26·0**	**−1·8**	**−8·0**	**−5·4**
Hargreaves, new CN	220·4	5·9	13·8	19·7	−48·7	−14·1	−28·5
Hargreaves, old CN	220·4	12·4	14·6	27·0	8·7	−9·2	−1·7

[a] Calibrated best results are shaded for each HUC. Negative values indicate underestimation.

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we selected. This low annual precipitation could also be viewed as less frequent rainfall events, which prevents a better estimation of the depletion coefficient and, therefore, gives poor predictions of runoff. In summary, for shallow and low-storage soils the newly developed CN method gives better results than its counterpart.

Which evapotranspiration method is better for shallow and low-storage soils?

From the best-calibrated results for each HUC (values highlighted in bold in Table II), it is apparent that the Penman–Monteith method performs better than the Hargreaves method except for HUC 03 090 204, which had the highest annual average precipitation among the HUCs selected for the study. The literature suggests that Penman–Monteith (based on energy balance) is a better method than Hargreaves (simple empirical) in estimating ET. This is also evidenced by this study. Therefore, better results in runoff are obtained when the Penman–Monteith method is used for estimating ET. When the rainfall becomes too high and the Penman–Monteith ET method is used (in combination with the new CN method), it appears that subsurface flow and water yield are overestimated. Although our study has shown these kinds of results, additional evidence from other studies is needed to substantiate this.

Different combinations of evapotranspiration–curve number methods

Based on the results obtained from this study, it appears that the Penman–Monteith ET estimation method in combination with the new CN method is the best way to calibrate watersheds dominated by shallow soils. For soils with low storage, no conclusive combination could be identified because the two HUCs tested show inconsistent results, and this was possibly because of the major differences in the hydrologic behaviour of soils under very high and very low rainfall conditions.

CONCLUSIONS

A one-parameter evapotranspiration and precipitation based continuous soil moisture accounting procedure is developed for the use of the SCS CN procedure for continuous hydrologic simulation. The procedure developed is incorporated into two widely used models, i.e. APEX and SWAT. Four eight-digit watersheds (HUCs) having different hydrologic conditions were used to study the newly developed CN method for analysing the parameter sensitivity and the behaviour of the new CN method with two different ET methods. The Hargreaves and Penman–Monteith evapotranspiration methods were used with two CN methods (existing and the newly developed) in four different combinations. A national-level dataset along with the HUMUS/SWAT model set-up is used for model simulations. From the results obtained, the following conclusions can be drawn:

1. Under shallow soil conditions, the newly developed CN method performs better than the existing CN method in predicting annual water balance components.
2. Parameterization for calibration is relatively easier with the new CN method than the existing CN method.
3. For a particular ET–CN (new CN method) combination, surface runoff and subsurface flow are very sensitive and ET is less sensitive to variations in the depletion coefficient parameter of the new CN method.
4. It appears that, under shallow soil conditions, the Penman–Monteith ET estimation method in combination with the new CN method can provide better results than the other combinations tested in this study.
5. Selection of a suitable ET–CN combination for hydrologic modelling depends on the nature of the study area in terms of hydrology, climate, land cover and extent of parameterization needed for calibration.

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